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RESEARCH ARTICLE

Changing landscapes by damming: the Three Gorges Dam causes downstream lake shrinkage and severe droughts

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Abstract

Context The world's largest dam—the Three Gorges Dam (TGD)—has been in operation for more than 10 years. While the recent shrinkage of large lakes and increased severe droughts in the downstream have been subjectively ascribed to TGD, empirical support based on thorough analysis is still lacking, leaving a gap for ecologists to quantify the TGD impacts on the surrounding landscapes.

Objectives This study aims to quantify the impacts of TGD water impoundment on downstream landscapes in terms of lake shrinkage and severe droughts.

Methods We have incorporated the recent findings and conducted a comprehensive analysis based on long-term datasets and contrasting scenarios with and without the presence of TGD. The datasets were constructed from hydrological measurements, a hydrodynamic model, and satellite data retrieval techniques.

Results Here we show that, in addition to natural variations due to climatic conditions, TGD water impoundment has indeed weakened river's ability in preventing backflows from its connected lakes directly contributed to their shrinkage. The impoundment substantially increased the intensity and severity of droughts downstream, and may have produced a cluster of impacts on the changing landscape.

Conclusions Our finding provides needed information for assessing TGD's impacts on environmental services in the region, and raises serious concerns with the ongoing large-scale hydraulic project—China's South-to-North Water Transfer Project—which will further reduce the flow of the Yangtze River.

Keywords Three Gorges Dam · Human activity · Landscape process

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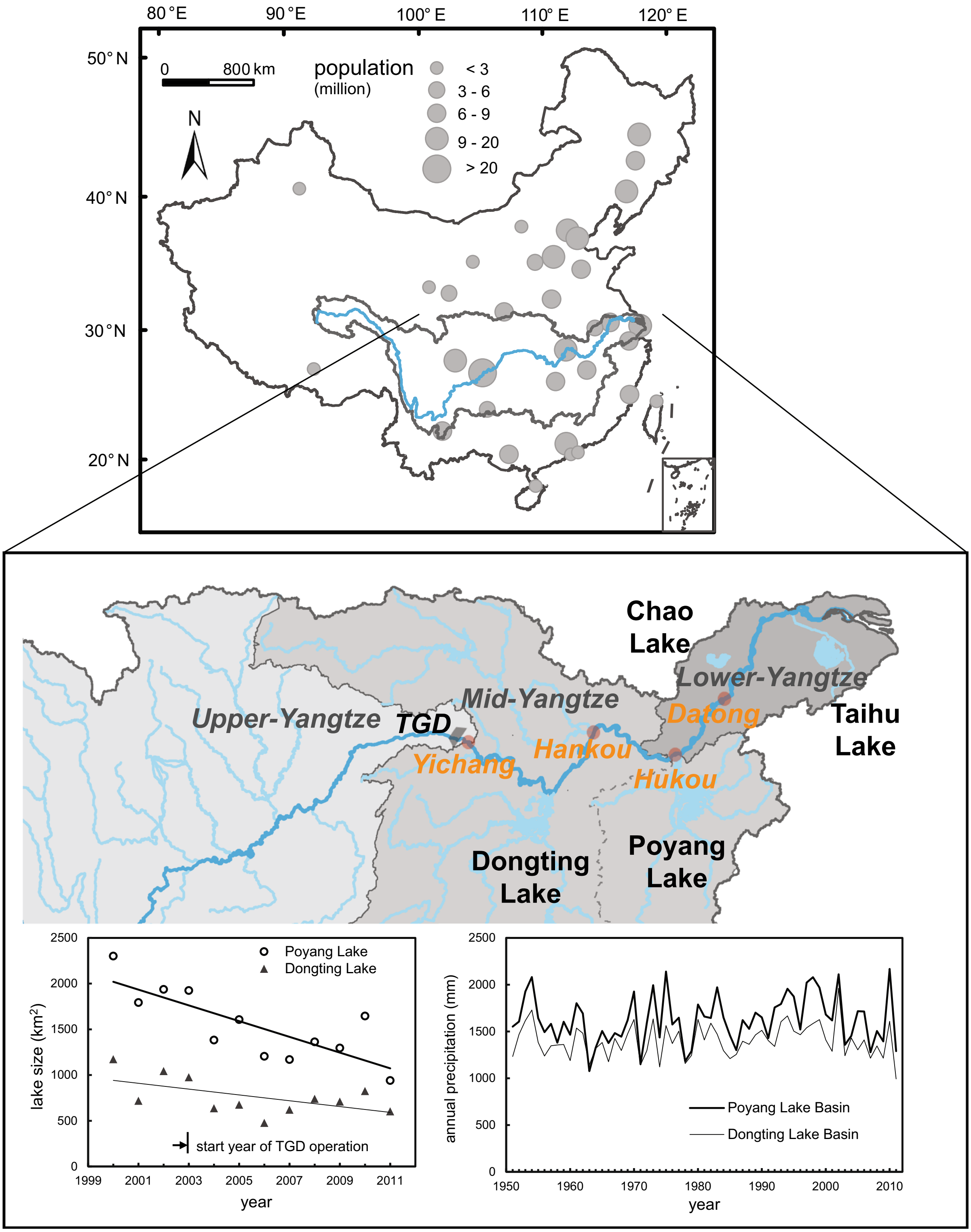
Introduction

The Three Gorges Dam (TGD) on the Yangtze River of China (Fig. 1) is the world's largest, most expensive, and most powerful hydro-power project to date (Wu et al. 2003, 2004; Stone 2008; Tullos 2009; Fu et al. 2011; Dai and Liu 2013). The Yangtze River is the largest in Asia and third in the world in terms of length and streamflow (Yang et al. 2007). The drainage basin downstream from TGD covers an area of 0.8 million km^2—more than two times larger than Germany. The river accounts for 36.5 % of China's water resources and supports nearly one-third of its population (Fig. 1). The river basin, extremely rich in wetlands, generates 40 % of China's GDP (Yang et al. 2009).


80 °E
90 °E
100° E
110° E
120° E
50° N
40° N
30° N
20° N
0
800 km
N
population
(million)
< 3
3 - 6
6 - 9
9 - 20
> 20
Chao Lake
Lower-Yangtze
Mid-Yangtze
Upper-Yangtze
TGD
Datong
Hankou
Yichang
Hukou
Taihu Lake
Dongting Lake
Poyang Lake
Poyang Lake
Dongting Lake
lake size (km²)
start year of TGD operation
year
annual precipitation (mm)
Poyang Lake Basin
Dongting Lake Basin
year

◀**Fig. 1** The Yangtze River basin and the location of the Three Gorges Dam (TGD). The entire Yangtze River basin is divided into the upper, middle, and lower reaches, demarcated by Yichang and Hukou. The Yangtze River historically has been a major source of water for several downstream lakes. Four of the five largest freshwater lakes in China—Poyang Lake, Dongting Lake, Taihu Lake, and Chao Lake—are located in the middle and lower reaches

Since the operation of TGD in 2003, lakes downstream such as Poyang Lake (the largest freshwater lake in China) and Dongting Lake have been shrinking (Fig. 1) at a faster rate, and severe droughts have become more frequent than that in previous decades (Jiao 2009; Hervé et al. 2011; Huang et al. 2012; Liu et al. 2013; Wang et al. 2014; Hu et al. 2015), resulting in significant hydrological, ecological, and socioeconomic consequences in spatial pattern and temporal process (Yang et al. 2011; Nicol et al. 2013; Roach and Griffith 2015) and increasing concerns to China and the world (WMO 2011). The diverse alternations are primarily attributable to climate change and/or anthropogenic influences (Hopkins et al. 2014; Lima et al. 2014; Liu and Wu 2016). Because the regional annual precipitation has not shown a decreasing trend during the past century (Fig. 1) (Xu et al. 2010; Yang et al. 2010; Chen et al. 2014), some have blamed TGD for the shrinking lakes and increasing frequency of severe droughts downstream (Lu et al. 2011; Qiu 2011; Feng et al. 2013; Huang et al. 2014; Zhang et al. 2014). However, empirical evidence is lacking (Lu et al. 2011). In the context of landscape ecology, quantifying human activity in shaping the dynamic landscape is a key topic in theory and practice, which helps develop holistic policies for sustaining ecosystem services in the changing landscape (Wu and Hobbs 2002; Wu 2013).

To shed light on this debate, we have incorporated the recent findings and conducted a comprehensive analysis based on long-term datasets and contrasting scenarios with and without the presence of TGD. The datasets were constructed from hydrological measurements, a hydrodynamic model, and satellite data retrieval techniques. Our paper aims to answer three interrelated questions: (1) To what extent did TGD water impoundment influence the downstream hydrologic regime? (2) Was the impoundment by TGD responsible for the shrinkage of the lakes freely connected with the river? (3) Did TGD actually affect the post-dam mainstream and downstream droughts?

Materials and methods

Data on daily river flow and water level at Yichang, Hankou, Hukou and Datong from 1 January 1960 to 31 December 2011 were obtained from the Hydrological Bureau of the Yangtze River Water Resources Commission. Daily inflow and outflow data of TGD between 1 June 2002 and 31 December 2011 were from China Three Gorges Corporation (http://www.ctg.com.cn/inc/sqsk.php). Morlet wavelet analysis (Goupillaud et al. 1984) was used to analyze periodic variations of streamflow as the method is suitable for non-stationary hydrologic processes in the context of climate change (Khaliq et al. 2006). The CHAM-Yangtze model was applied to calculate the downstream water level without TGD (Lai et al. 2013). Standardized runoff index (SRI), defined as the difference of streamflow from the mean divided by the standard deviation for a given period (Shukla and Wood 2008), was applied to identify the intensity of streamflow droughts based on monthly discharge at Datong for the cases with and without TGD. According to SRI, three classes of streamflow droughts are categorized: extreme drought $(-\infty, -2.0]$, severe drought $(-2.0, -1.5]$, and moderate drought $(-1.5, -1.0]$ (Mckee et al. 1993; Shukla and Wood 2008). Subsequently, drought severity was calculated, defined as the sum of all the monthly SRI values within the duration of a drought event. The water surface area of Poyang Lake was estimated using multi-temporal satellite (MODIS) data between January 2000 and December 2011 (Wu and Liu 2015). Lake water storage was calculated based on water surface maps and a 1:25,000 topographic map generated with field measurements in 2009. The calculated water storage (y) and water level (x) data were fitted with $y = 0.0037x^{3.6878}$ ($R^2 = 0.8478$, n = 192, P < 0.01), and applied to estimate changes in lake water storage due to changes in lake water level.

Results

The Three Gorges Reservoir has a water storage capacity of 393×10^8 m^3 (Fu et al. 2011), equivalent to the total volume of China's four largest freshwater lakes combined (Poyang Lake, Dongting Lake, Taihu Lake and Cao Lake) (Fig. 1) (Gao and Jiang 2012).

The post-dam river flow increased slightly for the 1-, 3-, 7-, 30- and 90-day minimum values at Yichang, Hankou and Datong (Gao et al. 2012, 2013). In contrast, the 1-, 3-, 7-, 30- and 90-day maximum values decreased significantly. At Hukou which is the separation point between the middle and the lower Yangtze reaches, the post-dam water level followed the similar pattern of change, and the annual mean water level decreased from 13.0 to 12.3 m. The monthly water level generally declined, except for March, with the largest drop occurring in October from 14.7 to 12.5 m ($P = 0.004$) and November from 12.1 to 9.9 m ($P = 0.002$). The decrease in the mainstream flow was attributable to both the current dry phase of a dry-wet cycle that started in 2003, as revealed from our Morlet wavelet analysis, and the water impoundment by TGD, as identified from our analysis using a CHAM-Yangtze model (Lai et al. 2014).

From 2003, TGD began to store water towards its designed full capacity via three stages (Table 1). During the first stage, the water level at TGD increased from 69.5 to 135.9 m above the sea level, impounding 121.5×10^8 m^3 of water between 9 April and 11 June 2003. This lowered the water level at Hukou by 0.46 ± 0.88 m. During the second stage, the water level at TGD rose from 135.4 to 155.7 m, impounding 106.8×10^8 m^3 of water from 20 September to 28 October 2006. This impoundment led to a drop in the water level at Hukou by 0.98 ± 0.50 m. During the third stage, as the water level at TGD increased from 145.3 to 172.4 m, impounding 192.5×10^8 m^3 of water from 28 September to 5 November 2008, the water level at Hukou decreased by 1.17 ± 0.60 m. Since 2009, TGD has routinely impounded water from 145 m to 175 m in autumn and then gradually released it to 145 m before the flood-prone season in March. The annually regulated water by the dam, approximately 200×10^8 m^3, is 50×10^8 m^3 more than the total water storage of Poyang Lake. Thus, impounding water by TGD for one to two months has resulted in a significant decrease in the water level downstream (Guo et al. 2012; Wang et al. 2013; Lai et al. 2014; Zhang et al. 2014; Mei et al. 2015a).

To address the second question, we quantified the variability in the water storage of Poyang Lake which is connected to the Yangtze River solely via the outlet at Hukou. The lake has an average depth of 8 meters, with its maximum water surface area occurring in late July and the minimum in December. The water level of Poyang Lake historically has been controlled primarily by the dynamics of inflow from and backflow to the Yangtze River, as well as the discharges from five other rivers in the Poyang Lake basin (Shankman et al. 2006). In the last five decades, the lake has shrunk in size, and land reclamation was found responsible for the shrinkage before the 1998 severe flooding (Shankman et al. 2006). Since then, the lake has continued to shrink from 3617 to 2336 km^2 in high-water period of 2011 (Liu et al. 2011, 2013; Wu and Liu 2015). Our analysis reveals that the surface area of Poyang Lake in September was significantly correlated with the water level at Hukou ($R^2 = 0.5732$, $n = 10$, $P < 0.05$), indicating that the shrinkage of Poyang Lake was attributable to the decreased water level of the Yangtze River allowing more water to flow out of the lake (Feng et al. 2013; Liu et al. 2013; Zhang et al. 2014; Liu and Wu 2016). While the post-dam water level decline has resulted from both regional climate variations and TGD, the latter has evidently affected the water storage of Poyang Lake (Table 1). Specifically, the net water loss of the lake was 12.9×10^8 m^3 during the first stage of TGD impoundment in 2003, 12.3×10^8 m^3 during the second stage in 2006, 32.5×10^8 m^3 during the third stage in 2008, 16.4×10^8 m^3 in 2009, 17.9×10^8 m^3 in 2010, and 13.2×10^8 m^3 in 2011. Together, the water outflow accounted for 3–51 % of the lake's water storage for all TGD impoundment periods. The water loss may have been responsible for the shrinkage of lakes (Feng et al. 2013; Liu et al. 2013; Zhang et al. 2014; Mei et al. 2015b) and the pattern change of protected wetlands (Zhang et al. 2012), as well as decreased water availability for agricultural lands that support millions of people in the region (Shankman et al. 2006; Wu and Liu 2015).

To address the third question, we conducted a rigorous scenario analysis for the Yangtze River droughts with and without TGD. For the first stage of TGD impoundment in 2003, SRI changed from -0.06 without TGD to -0.34 with TGD, indicating a hydrologic shift from a normal to a dry state ($0 > \mathrm{SRI} > -1.0$). For the second stage in 2006, SRI was -2.27 without TGD and -2.67 with TGD. Based on their corresponding probabilities (0.0116 and 0.0038) and reciprocals (86 and 263), we estimated that the magnitude of a once-in-7-years drought was intensified to that of a once-in-22-years

Table 1 Three Gorges Dam (TGD) impoundments and hydrologic effects downstream

TGD impoundment				Hydrologic effects at Hukou			
Starting and ending date	Duration (days)	Water level change (m)	ΔWater storage ($10^8 m^3$)	ΔWater level (m)	ΔPoyang Lake storage ($10^8 m^3$) (% lake water loss)	SRI without TGD (probability)	SRI with TGD (probability)
04/09 to 06/11, 2003	63	69.5 → 135.9	121.5	−0.46 ± 0.88	−12.9 (28 %)	−0.06 (0.4761)	−0.34 (0.3669)
10/26 to 11/15, 2003	20	135.5 → 138.8	13.8	−0.44 ± 0.38	−3.5 (6 %)	−1.12 (0.1314)	−1.29 (0.0985)
09/30 to 10/15, 2004	15	135.6 → 138.7	13.4	−0.06 ± 0.03	−1.4 (3 %)	−0.32 (0.3745)	−0.36 (0.3794)
09/30 to 10/04, 2005	4	135.6 → 138.8	13.7	−0.02 ± 0.01	−0.6 (1 %)	−0.06 (0.4761)	−0.06 (0.4761)
09/20 to 10/28, 2006	38	135.4 → 155.7	106.8	−0.98 ± 0.50	−12.3 (51 %)	−2.27 (0.0116)	−2.67 (0.0038)
09/24 to 10/31, 2007	37	144.8 → 155.8	64.3	−0.58 ± 0.36	−12.7 (26 %)	−0.66 (0.2546)	−0.74 (0.2296)
09/28 to 11/05, 2008	38	145.3 → 172.4	192.5	−1.17 ± 0.60	−32.5 (35 %)	−0.41 (0.3409)	−0.74 (0.2296)
09/14 to 10/30, 2009	46	145.6 → 170.9	177.3	−1.43 ± 0.72	−16.4 (47 %)	−1.69 (0.0455)	−2.23 (0.0129)
08/26 to 10/26, 2010	61	146.2 → 175.0	212.2	−0.43 ± 0.28	−17.9 (25 %)	0.15 (0.5596)	−0.13 (0.4483)
08/21 to 11/07, 2011	79	146.2 → 175.1	230.9	−0.79 ± 0.45	−13.2 (36 %)	−1.32 (0.0934)	−1.82 (0.0344)

drought (Lloyd-Hughes and Saunders 2002). For the third stage in 2008, SRI increased from −0.41 without TGD to −0.74 with TGD, indicating an increased possibility towards a drier state. SRI increased from −1.69 to −2.23 in 2009, indicating an extreme drought intensified from a severe drought, and from −1.32 to −1.82 in 2011, signifying a severe drought strengthened from a moderate drought. It suggests that the TGD impoundments did intensify the droughts and change the frequency of drought classes.

In addition to increasing drought magnitude, TGD impoundments that operated for one to two months also affected drought severity. Since the operation of TGD in 2003, seven moderate to extreme droughts (SRI < −1.0) have occurred, with drought severity ranging from −3.26 to −12.39 (Table 2). The 2011 extreme drought was the most severe, followed by two other extreme droughts in 2006–2007 and 2003–2004, respectively. Comparison between the cases with and without TGD indicates that TGD resulted in a substantial increase in the drought severity of severe drought events. On the other hand, the severity of the severe drought in spring 2007 was mitigated moderately by water release from TGD.

Discussion

Overall, our results strongly indicate that, although it is not the only cause, TGD has significantly

Table 2 Post-dam drought events and their severity

Drought period	Drought severity		Rank order
	Without TGD	With TGD	
11/2003 to 12/2004	−8.02	−8.10	3
05/2006 to 01/2007	−10.56	−11.22	2
04/2007 to 07/2007	−5.37	−5.36	5
10/2007 to 12/2007	−3.10	−3.26	7
05/2008 to 08/2008	−3.58	−3.60	6
4/2009 to 12/2009	−6.29	−6.91	4
03/2011 to 11/2011	−11.67	−12.39	1

contributed to the shrinkage of the largest freshwater lake of China and the increase in the frequency and magnitude of downstream droughts. While dam construction is responsible for migratory fish extinction in some rivers (Hall et al. 2011; Melles et al. 2015), lake reduction in size and number alters the aquatic environment and surrounding landscapes as biotic habitats (Nicol et al. 2013). Indeed, the TGD-induced hydrological change altered the inundation patterns of Poyang Lake, and this may have produced a cluster of unfavorable impacts on the wetland ecosystem, such as plants' seed germination, seeding development, species composition and their spatial distribution, and availability of forging sites for migratory birds (Zhang et al. 2012; Wu and Liu 2015).

On the other hand, our study also suggests that properly scheduling the TGD operations may mitigate drought severity by releasing water during a drought period. Such drought-oriented management of TGD is necessary to minimize its negative environmental and socioeconomic impacts and help sustainable development in the Yangtze River basin. Our estimated water loss from lakes may serve as an important basis for designing ecological compensation measures. More importantly, the cause-and-effect chain between the TGD operation and downstream lake change offers a critical clue to optimize the dynamic pattern of wetlands for sustainable ecosystem services (Jiang et al. 2015), yet it remains as a grand challenge for landscape ecology (Wu and Hobbs 2002; Wu 2013). In addition, inter-annual, decadal, and long-term variations in hydrologic conditions, as well as influences of climate change (Milly et al. 2008), should be taken into consideration in designing and implementing a scientifically sound water regulation plan for TGD.

Furthermore, the post-dam effects of TGD should be heeded as important lessons for a number of huge hydraulic projects in China, particularly the South-to-North Water Transfer Project (SNWTP) operated since December 2014. The water delivery of about 100×10^8 m^3 from the mid-Yangtze to North China (Chen and Xie 2010) will most likely further worsen the current situation of downstream lake shrinkage, severe droughts and surrounding landscapes.

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